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Belle time-integrated ϕ_3 (γ) measurements

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We report recent results by the Belle collaboration on the determination of the CP-violating angle ϕ_3 (γ) using time-integrated methods.

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1 Introduction

Precise measurements of the parameters of the standard model are fundamentally important and may reveal new physics. The Cabibbo-Kobayashi-Maskawa (CKM) matrix [1, 2] consists of weak-interaction parameters for the quark sector, and the phase ϕ_3 (also known as γ) is defined by the elements of the CKM matrix as $\phi_3 \equiv \arg\left(-V_{ud}V_{ub}{}^*/V_{cd}V_{cb}{}^*\right)$. This phase is less accurately measured than the two other angles ϕ_1 (β) and ϕ_2 (α) of the unitarity triangle.*

In the usual quark phase convention where large complex phases appear only in V_{ub} and V_{td} [3], the measurement of ϕ_3 is equivalent to the extraction of the phase of V_{ub} relative to the phases of other CKM matrix elements except for V_{td}. Figure 1 shows the diagrams for $B^- \to \bar{D}^0 K^-$ ($b \to u$) and $B^- \to D^0 K^-$ ($b \to c$) decays.† By analyzing the interfering processes produced when $\bar{D}^0$ and D^0 decay to the same final states, we extract ϕ_3 as well as relevant dynamical parameters. We define the magnitude of the ratio of amplitudes $r_B = |A(B^- \to \bar{D}^0 K^-)/A(B^- \to D^0 K^-)|$ and the strong phase difference $\delta_B = \delta(B^- \to \bar{D}^0 K^-) - \delta(B^- \to D^0 K^-)$, which are crucial parameters needed in the extraction of ϕ_3. In this report, we show recent results by the Belle collaboration on the determination of ϕ_3.

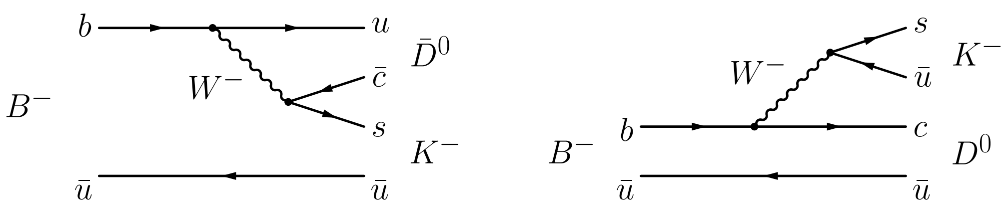

Figure 1: Diagrams for the $B^- \to \bar{D}^0 K^-$ and $B^- \to D^0 K^-$ decays.

2 Result for $B^- \to D^{(*)} K^-$, $D \to K_S \pi^+ \pi^-$

One of most promising ways of measuring ϕ_3 uses the decay $B^- \to DK^-$, $D \to K_S\pi^+\pi^-$ [4, 5], where D indicates $\bar{D}^0$ or D^0. The method is based on the fact that the amplitudes for $B^\pm$ can be expressed by

$$M_\pm = f(m_\pm^2, m_\mp^2) + r_B e^{\pm i\phi_3 + i\delta_B} f(m_\mp^2, m_\pm^2), \tag{1}$$

where $m_\pm^2$ are defined as Dalitz plot variables $m_\pm^2 \equiv m_{K_S\pi^\pm}^2$, and $f(m_+^2, m_-^2)$ is the amplitude of the $\bar{D}^0 \to K_S\pi^+\pi^-$ decay. By applying a fit on $m_\pm^2$, ϕ_3 is extracted with

* The angles ϕ_1 and ϕ_2 are defined as $\phi_1 \equiv \arg\left(-V_{cd}V_{cb}{}^*/V_{td}V_{tb}{}^*\right)$ and $\phi_2 \equiv \arg\left(-V_{td}V_{tb}{}^*/V_{ud}V_{ub}{}^*\right)$.

† Charge conjugate modes are implicitly included unless otherwise stated.

r_B and δ_B. The decay $B^- \to D^* K^-$ can also be used by reconstructing D^* from $D\pi^0$ or $D\gamma$, for which the parameters r_B^* and δ_B^* are introduced.

The result [6] is based on a data sample that contains 6.6×10^8 $B\bar{B}$ pairs. The amplitude $f(m_+^2, m_-^2)$ is obtained by a large sample of $\bar{D}^0 \to K_S \pi^+ \pi^-$ decays produced in continuum e^+e^- annihilation, where the isobar model is assumed with Breit-Wigner functions for resonances. The background fractions are determined depending on $\Delta E \equiv E_B - E_{\rm beam}$, $M_{\rm bc} \equiv \sqrt{E_{\rm beam}^2 - |\vec{p}_B|^2}$, and event-shape variables for suppressing the $e^+e^- \to q\bar{q}$ ($q = u, d, s, c$) background, where E_B ($\vec{p}_B$) and $E_{\rm beam}$ are defined in the e^+e^- center-of-mass frame as the energy (the momentum) of the reconstructed B candidates and the beam energy, respectively. Using obtained amplitude $f(m_+^2, m_-^2)$ and background fractions, the fit on $m_\pm^2$ is performed with the parameters $x_\pm = r_\pm \cos(\pm\phi_3 + \delta_B)$ and $y_\pm = r_\pm \sin(\pm\phi_3 + \delta_B)$, where we take r_B separately for $B^\pm$ as $r_\pm$. The results are shown in Figure 2 for $B^- \to DK^-$ and $B^- \to D^*K^-$. The separations with respect to the charges of $B^\pm$ indicate an evidence of the CP violation. From the results of the fits, we measure

$$\phi_3 = 78.4^\circ \ {}^{+10.8^\circ}_{-11.6^\circ}(\text{stat}) \pm 3.6^\circ(\text{syst}) \pm 8.9^\circ(\text{model}) \tag{2}$$

as well as $r_B = 0.161 \ {}^{+0.040}_{-0.038} \pm 0.011 \ {}^{+0.050}_{-0.010}$, $r_B^* = 0.196 \ {}^{+0.073}_{-0.072} \pm 0.013 \ {}^{+0.062}_{-0.012}$, $\delta_B = 137.4^\circ \ {}^{+13.0^\circ}_{-15.7^\circ} \pm 4.0^\circ \pm 22.9^\circ$, and $\delta_B^* = 341.7^\circ \ {}^{+18.6^\circ}_{-20.9^\circ} \pm 3.2^\circ \pm 22.9^\circ$. The model error is due to the uncertainty in determining $f(m_+^2, m_-^2)$. Note that it is possible to eliminate this uncertainty using constraints obtained by analyzing $\psi(3770) \to D^0\bar{D}^0$ [7].

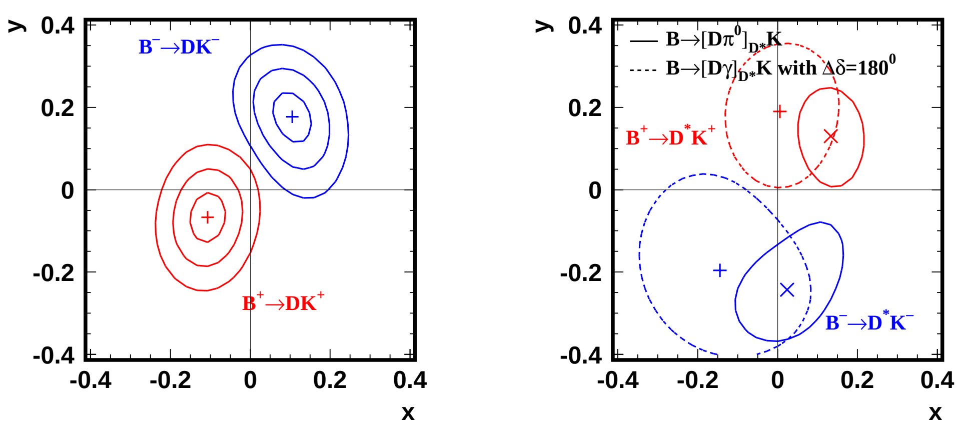

Figure 2: Results of the fits for $B^- \to DK^-$ (left) and $B^- \to D^*K^-$ (right) samples, where the contours indicate 1, 2, and 3 (left) and 1 (right) standard-deviation regions.

3 Result for $B^- \to DK^-$, $D \to K^+\pi^-$

The effect of CP violation can be enhanced, if the final state of the D decay following to the $B^- \to DK^-$ is chosen so that the interfering amplitudes have comparable magnitudes [8]. The decay $D \to K^+\pi^-$ is a particularly useful mode; the usual observables are the partial rate $\mathcal{R}_{DK}$ and the CP-asymmetry $\mathcal{A}_{DK}$ defined as

$$\begin{aligned}
\mathcal{R}_{DK} &\equiv \frac{\mathcal{B}(B^- \to [K^+\pi^-]_D K^-) + \mathcal{B}(B^+ \to [K^-\pi^+]_D K^+)}{\mathcal{B}(B^- \to [K^-\pi^+]_D K^-) + \mathcal{B}(B^+ \to [K^+\pi^-]_D K^+)} \\
&= r_B^2 + r_D^2 + 2 r_B r_D \cos(\delta_B + \delta_D) \cos\phi_3, \qquad (3) \\
\mathcal{A}_{DK} &\equiv \frac{\mathcal{B}(B^- \to [K^+\pi^-]_D K^-) - \mathcal{B}(B^+ \to [K^-\pi^+]_D K^+)}{\mathcal{B}(B^- \to [K^+\pi^-]_D K^-) + \mathcal{B}(B^+ \to [K^-\pi^+]_D K^+)} \\
&= 2 r_B r_D \sin(\delta_B + \delta_D) \sin\phi_3 / \mathcal{R}_{DK}, \qquad (4)
\end{aligned}$$

where $[f]_D$ indicates that the state f originates from a D meson, $r_D = |A(D^0 \to K^+\pi^-)/A(D^0 \to K^-\pi^+)|$, and $\delta_D = \delta(D^0 \to K^-\pi^+) - \delta(D^0 \to K^+\pi^-)$. For the parameters r_D and δ_D, external experimental inputs can be used [9].

In this report, we show a preliminary result based on a data sample that contains 7.7×10^8 $B\bar{B}$ pairs (the full data sample collected by Belle at $\Upsilon(4S)$ resonance). The decay $B^- \to D\pi^-$ is also analyzed similarly as a reference mode. For the largest background from the continuum process $e^+e^- \to q\bar{q}$, we apply the new method of the discrimination based on NeuroBayes neural network [10]. The inputs are a Fisher discriminant of modified Super-Fox-Wolfram moments, cosine of the decay angle of $D \to K^+\pi^-$, vertex separation between the reconstructed B and the remaining tracks, and seven other variables. The signal is extracted by a two-dimensional fit on ΔE and NeuroBayes output ($\mathcal{NB}$), where we simultaneously fit for DK^-, DK^+, $D\pi^-$, and $D\pi^+$, as shown in Figure 3. As a result, we obtain

$$\begin{aligned}
\mathcal{R}_{DK} &= [1.62 \pm 0.42(\text{stat})\ ^{+0.16}_{-0.19}(\text{syst})] \times 10^{-2}, \qquad (5) \\
\mathcal{A}_{DK} &= -0.39 \pm 0.26(\text{stat})\ ^{+0.06}_{-0.04}(\text{syst}), \qquad (6) \\
\mathcal{R}_{D\pi} &= [3.28 \pm 0.37(\text{stat})\ ^{+0.22}_{-0.23}(\text{syst})] \times 10^{-3}, \qquad (7) \\
\mathcal{A}_{D\pi} &= -0.04 \pm 0.11(\text{stat})\ ^{+0.01}_{-0.02}(\text{syst}), \qquad (8)
\end{aligned}$$

where the first evidence of the suppressed DK signal is obtained with a significance 3.8σ including systematic error. Our study will make a significant contribution to a model-independent extraction of ϕ_3 by combining relevant observables, e.g., the partial rates and the CP-asymmetries for $D \to CP$ eigenstates [11].

4 Conclusion

In conclusion, recent results on the decays $B^- \to D^{(*)}K^-$ followed by $D \to K_S\pi^+\pi^-$ and $D \to K^+\pi^-$ are reported. By the Dalitz-plot analysis for $D \to K_S\pi^+\pi^-$, the value

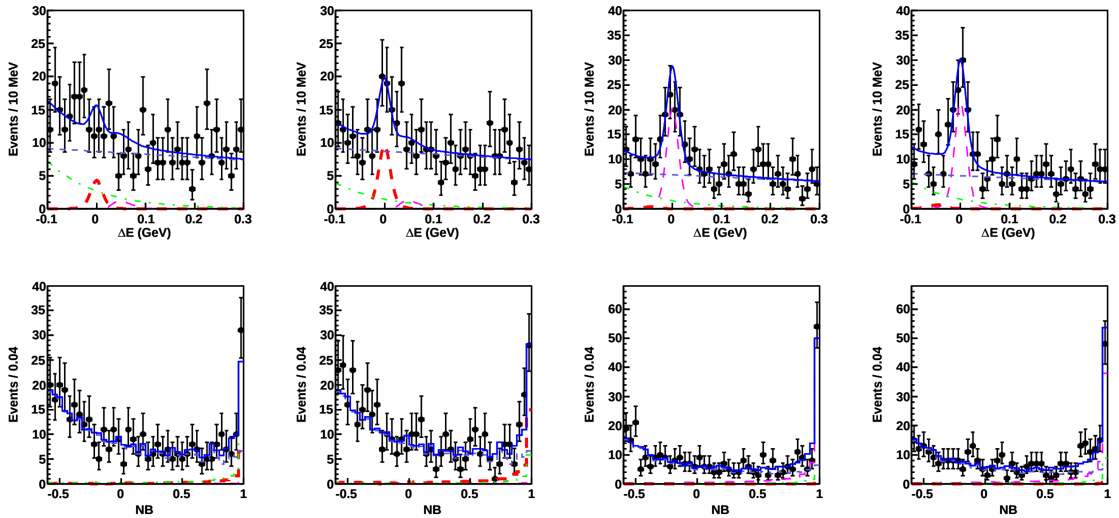

Figure 3: The distributions of ΔE for $\mathcal{NB} > 0.5$ (top) and $\mathcal{NB}$ for $|\Delta E| < 40$ MeV (bottom) on the suppressed modes DK^-, DK^+, $D\pi^-$, and $D\pi^+$ from left to right. The components are thicker long-dashed red (DK), thinner long-dashed magenta ($D\pi$), dash-dotted green ($B\bar{B}$ background), and dashed blue ($q\bar{q}$ background).

of ϕ_3 is measured to be $\phi_3 = 78.4^\circ\ {}^{+10.8^\circ}_{-11.6^\circ}(\mathrm{stat}) \pm 3.6^\circ(\mathrm{syst}) \pm 8.9^\circ(\mathrm{model})$. For $D \to K^+\pi^-$, preliminary results on the partial rate $\mathcal{R}_{DK}$ and the CP-asymmetry $\mathcal{A}_{DK}$ are reported, where the first evidence of the signal is obtained with a significance 3.8σ.

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